

Discovery of a spiral-host episodic radio-galaxy

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Accepted. Received

ABSTRACT

We report the discovery of a unique radio galaxy at $z=0.137$, which could possibly be the second spiral-host large radio galaxy and also the second triple-double episodic radio galaxy. The host galaxy shows signs of recent star formation in the UV but is optically red and is the brightest galaxy of a possible cluster. The outer relic radio lobes of this galaxy, separated by ~ 1 Mpc, show evidence of spectral flattening and a high fraction of linear polarisation. We interpret that these relic lobes have experienced re-acceleration of particles and compression of the magnetic field due to shocks in the cluster outskirts. From the morphology of the relics and galaxy distribution, we argue that re-acceleration is unlikely to be due to a cluster-cluster merger and speculate about the possibility of accretion shocks. The source was identified from SDSS, GALEX, NVSS and FIRST survey data but we also present follow up optical observations with the Lulin telescope and 325 MHz low frequency radio observations with the GMRT. We briefly discuss the scientific potential of this example in understanding the evolution of galaxies and clusters by accretion, mergers, star formation, and AGN feedback.

Key words: galaxies: active – galaxies: evolution – galaxies: individual: SDSS J140948.85-030232.5 – galaxies: clusters: individual: MaxBCG J212.45357-03.04237 – cosmology: observations – acceleration of particles

1 INTRODUCTION

By incorporating processes of AGN feedback into the models of hierarchical structure formation, it is possible to explain observed galaxy population properties, such as the galaxy and cluster luminosity function, the M_\bullet – σ relation, and the colour-magnitude bi-modality of nearby galaxies (Springel, Di Matteo & Hernquist 2005, Croton et al. 2006). Powerful and large-scale feedback in the form of radio lobes seen as multiple cavities in X-ray images of clusters has provided strong support for such models (Nulsen et al. 2005, Sanders & Fabian 2007, Randall et al. 2011). Luminous radio galaxies are also found to be tracers of high- z cluster formation (Venemans et al. 2007, Zirm et al. 2005). In the nearby Universe, diffuse Mpc-scale shell-like radio emission found in the outskirts of clusters has been interpreted as emission from acceleration of particles at shock fronts due to cluster merg-

ers or structure formation (Ensslin et al. 1998; Ensslin et al. 2001; Bagchi et al. 2006, 2011; van Weeren et al. 2010).

Apart from mergers, clusters grow by accretion from cosmic galaxy filaments. Evidence of shocks, predicted for such accretion, is yet to be convincingly detected from X-ray observations, but many radio observations show promising prospects (Ensslin et al. 1998, Pfrommer, Ensslin & Springel 2008). A wide-angle tail radio galaxy recently discovered to be present in a several-Mpc-scale galaxy filament has been proposed as evidence of gas accretion through the filament onto the cluster (Edwards et al. 2010). Due to the Mpc-scale size and episodic nature of radio galaxies (Saikia & Jamroz 2009), whose relic plasma as old as 2 Gyr can be revived (Ensslin & Gopal-Krishna 2001), low frequency radio observations, naturally tracing old relativistic plasma, are powerful probes of these merger, accretion, and feedback processes driving cluster formation and evolution. The timescale of 1–2 Gyr is comparable to the dynamical timescale of galaxies in the clusters, the timescale of galaxy mergers, the timescale of the star formation in UV-bright early-type

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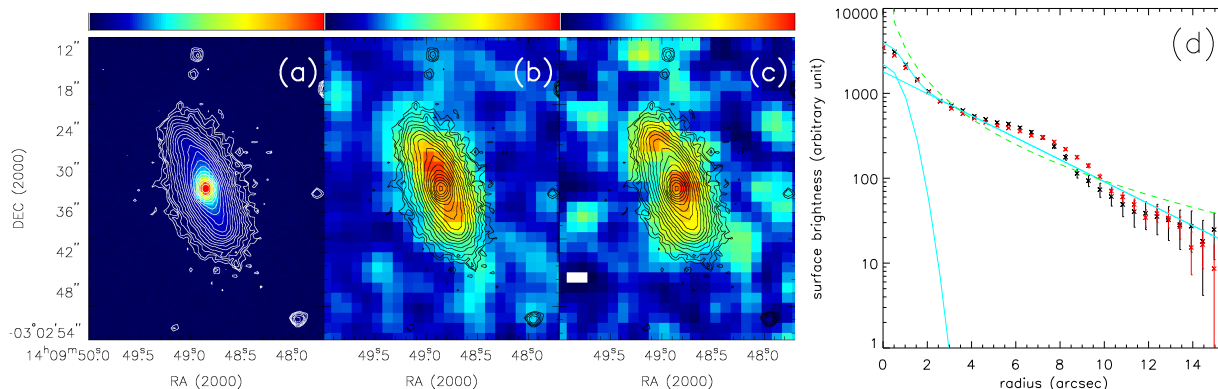


Figure 1. (a) Lulin *R*-band image of the host galaxy Speca, presented both in colour (linear scale) and contours (logarithmic scale). (b) The same *R*-band contours are superposed on the smoothed near-UV image from GALEX in linear scale. (c) The same *R*-band contours are superposed on the smoothed far-UV image also from GALEX in linear scale. (d) Radial surface brightness profile of the Lulin *R*-band image. Black and red data are shown for the SW and NE parts of the disk, respectively, for comparison. Fitted model profiles are of a nuclear point source and exponential disk (cyan continuous line) and of a de Vaucouleurs profile (green broken line). For the former model, both individual model components and the total are shown.

galaxies (Yi et al. 2005) and quenching of star formation in the post-starburst (E+A) galaxies (Goto 2005). Therefore, combined low-frequency study of relics of AGN feedback and recent star formation in AGN host galaxies is a potential new strategy of investigating galaxy-black hole co-evolution via mergers and feedback.

Here we report the discovery of a unique radio galaxy whose host galaxy appears to be a spiral or disk with young star formation, rather than a typical giant elliptical galaxy with a predominantly old stellar population. Equally unique is that it shows signs of three distinct episodes of jet ejection where the outer relic radio lobes, separated by ~ 1 Mpc, have experienced particle re-acceleration possibly due to shocks in the cluster outskirts. The optical source had been cataloged before as SDSS J140948.85-030232.5 or LCRS B140713.3-024824 or MaxBCG J212.45357-03.04237 (being brightest in the cluster) but for ease in referring we nicknamed it, due to its uniqueness, ‘Speca’ (SPiral-host Episodic Cluster-dominant AGN). For the spectroscopic redshift of Speca $z=0.1378$, 1 arcsec corresponds to 2.396 kpc, in a Universe with $H_0=71$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_m=0.27$ and $\Omega_{vac}=0.73$.

2 OBSERVATIONS AND DATA ANALYSIS

Optical imaging: Optical *R*-band (Bessell) observations were made on the night of 2010 May 16 (UT) with the Lulin One-meter telescope (LOT). A CCD camera (PI1300B; Kinoshita et al. 2005) with an EEV CCD36-40 chip was attached at the Cassegrain focus of the telescope to provide a pixel scale of 0.51 arcsec. We took 17 frames of 180 sec exposures, and they were processed in a standard manner (dark and bias subtraction, flat fielding with a sky flat, stacking with sigma clipping for cosmic-ray removal). The final stacked image of 3060 sec exposure has an effective (after stacking) seeing size of 1.5 arcsec (FWHM).

Radio continuum imaging: The galaxy was observed with the Giant Metrewave Radio Telescope (GMRT; Swarup et al. 1991) at 325 MHz on 2010 April 26 with a to-

tal bandwidth of 32 MHz and total time on the target galaxy ~ 5 hours. The data reduction was done mainly using AIPS++ (version: 1.9, build #1556). 3C48 was the primary flux density and bandpass calibrator. After applying bandpass corrections on the phase calibrator (1419+064), gain and phase variations were estimated, and then flux density, bandpass, gain and phase calibration from flux density and phase calibrators were applied on the target field. The standard procedure for radio continuum data analysis was followed and a final image was made after several rounds of phase self-calibration, and one round of amplitude self-calibration, where the data were normalized by the median gain for all the data. The final images resulted in an r.m.s. noise of 0.2 mJy beam $^{-1}$ and angular resolution of 9.75 arcsec \times 7.45 arcsec (Position Angle (P.A.)=63 $^\circ$). The low-resolution map prepared to match the beam size (45 arcsec) of NRAO VLA Sky Survey (NVSS) has a higher noise (1.4 mJy beam $^{-1}$). All the radio images presented in this letter have uniform leveling of contours, r.m.s noise \times (-4, -2.82, 2.82, 4, 5.65, 8... in steps of $\sqrt{2}$).

3 RESULTS AND DISCUSSION

3.1 Disk structure in the host galaxy

While comparing Sloan Digital Sky Survey (SDSS) and Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) images, we identified the host galaxy Speca as an unusual object. The galaxy lies at the geometrical centre of the radio lobes, and the SDSS spectrum from the central region shows a [NII]/H α line ratio higher than unity, suggesting it to be the AGN host galaxy. Our *R*-band image shows that the main body clearly suggests a morphology consistent with a nearly edge-on disk galaxy (Figure 1 (a)). The north-east (NE) side of the nucleus shows a curved feature similar to a spiral-arm seen nearly edge-on. Similar structure is also seen in SDSS *g'*, *r'* and *i'*-band images, but any possible counterpart of this spiral arm on the south-western side of the nucleus is not seen. The curved nature of the spi-

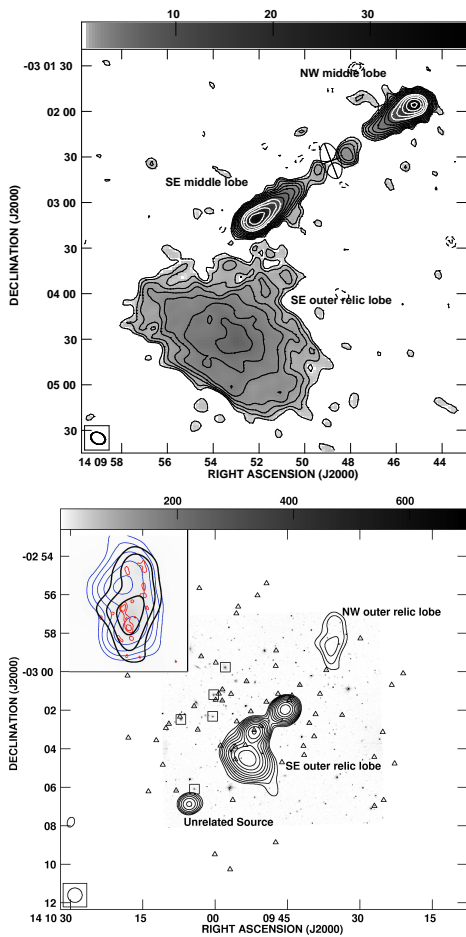


Figure 2. Top Panel: The high resolution (~ 9 arcsec) GMRT 325 MHz image, both in contour and grey-scale, of the inner, middle and SE outer relic lobes of Specula. The isophotal major-, minor-axis and P.A. of the host galaxy, as in the text, are also indicated with an ellipse and '+' sign. Bottom Panel: The low resolution (45 arcsec) GMRT 325 MHz image in contours is superposed on the R -band optical image. The relic lobes and an unrelated radio source are marked. The spectroscopically confirmed members of the cluster are marked by boxes, and possible members from SDSS z_{photo} are marked by triangles. The inset shows details of the NW outer relic lobe with NVSS data shown as blue contours, high resolution (~ 9 arcsec) GMRT 325 MHz image shown in red contours, and the low resolution (45 arcsec) 325 MHz image as in the background is shown in thick black contours.

ral arm-like feature and extended isophotal contours on the southern side, disfavours any mid-plane dust causing the observed stellar structure. Measured up to 25 mag arcsec $^{-2}$ in the SDSS r' -band, the size of the galaxy is 60×29 kpc (25 arcsec and 12 arcsec with P.A. 21°) suggesting that Specula is a large, mature host galaxy.

In Figure 1 (b, c) we also present a comparison of the R -band image with near-UV (NUV) and far-UV (FUV) images available on-line from the Galaxy Evolution Explorer (GALEX). Surprisingly, the UV emission (smoothed with a tophat kernel of radius 2 (4) pixels for NUV (FUV)) correlates nicely with the optical major-axis. The lack of dominant UV emission from the centre of the galaxy suggests that the emission is associated with star formation and unlikely to be dominated by the central AGN. In the NUV

the northern side is brighter than the southern side, consistent with the extinction being a possible cause behind the lack of a spiral-arm feature on the southern side. Additionally, we note that the optical colour is also redder for the southern side. UV images thus clearly demonstrate a young star-forming disk in Specula. From the UV color for the whole area of Specula (FUV-NUV ~ 0.43 in AB) and comparing with models of stellar population synthesis (Bruzual & Charlot 2003), we inferred that the star formation in Specula is younger than ~ 500 Myr. However, the $u'-r'$ colour (2.6 in AB), five band SED and nuclear spectrum from SDSS suggest a several Gyr old stellar population dominant in the host galaxy.

The surface brightness profile of the Lulin R -band image was analyzed with GALFIT version 2.03b (Peng et al. 2002). We explored both the exponential disk and de Vaucouleurs profile, with and without a nuclear Gaussian source. The best model was found to be an exponential disk model (effective radius = 5.3 arcsec, axial ratio = 0.35, P.A. = 17°) with an unresolved (within the errors) point source at the nucleus. The radial profile of the surface brightness is shown in Figure 1 (d) with our best model and the next best one (de Vaucouleurs profile without a nuclear source). The observed profile shows excess features on both the NE and SW sides of the nucleus at ~ 7 arcsec from the nucleus, making the fit unsatisfactory in terms of statistics even with our best model. However, the best model of disk with a nuclear point source is far better than the second best one since the latter predicts too much flux in both the inner and outer parts of the radial profile.

In summary, the optical and UV structure and optical radial brightness profile strongly support the identification of Specula as a rare radio galaxy hosted in a young star-forming spiral/disk galaxy. To the best of our knowledge, this is the second spiral-host large radio galaxy, after the only well-known case of 0313-192, discovered by Ledlow, Owen & Keel (1998). In light of recent HI studies finding large massive gas disks (Oosterloo et al. 2007) and UV studies finding young stellar disks in a large-fraction of early-type galaxies (Yi et al. 2005, Salim & Rich 2010), we speculate that the disk nature of Specula is due to recent star formation, possibly following a merger more than 500 Myr ago (e.g. NGC 3801; Hota et al. 2009, 2011).

3.2 Episodic radio jet activity

The possible episodic nature of this radio galaxy was first identified from comparisons of NVSS and FIRST images, where two prominent emission blobs on large scales seen in NVSS were found to be missing in FIRST. To investigate further we observed it with the GMRT at 325 MHz. We found typical 'edge-brightened' radio lobe structure as in FR II type radio galaxies (Figure 2 top panel). A similar radio structure is also seen in the higher frequency FIRST image, where the lobes have equal flux densities of 24 mJy (23.9 mJy for north-western (NW) and 23.8 mJy for south-eastern (SE)) within the errors. The projected linear size of the lobes, 307 kpc (peak to peak measured to be 128 arcsec aligned at P.A. of 306°), is typical of classical large radio galaxies. These components are hereafter referred to as 'middle lobes' of Specula. To our surprise, we also found two new peaks (2.24 mJy beam $^{-1}$ for NW peak and 1.34

mJy beam⁻¹ for SE peak) of radio emission with a peak to peak projected separation of ~ 50 kpc (22 arcsec) at a P.A. of 297° . The total flux densities of these blobs are 4.52 and 2.56 mJy for the NW and SE respectively. The position angle of the line joining these two peaks is $\sim 10^\circ$ offset from that defined by the middle lobes. Higher resolution and higher frequency images are required to confirm these peaks as radio lobes, but in comparison with B0925+420 (Brocksopp et al. 2007), we believe them to be lobes and refer as ‘inner lobes’. Interestingly, the inner lobes are located along the minor axis of the host galaxy but are larger than its optical extent (29 kpc) suggesting that the lobes have not formed due to interaction with the inter-stellar medium of the host galaxy (Figure 2 top panel).

A large diffuse emission blob to the south of the SE middle lobe, and almost connected, can be seen in Figure 2 (top panel). It shows a centrally peaked structure and the outer boundary on its SE side is almost straight with a sharp drop in surface brightness. The total extent of this diffuse emission is ~ 300 kpc, comparable to the full extent of the middle lobes. It shows an overall NE-SW elongation roughly orthogonal to the middle lobes. This emission blob was prominent in NVSS but was missing in FIRST. Because of this diffuse nature and no apparent optical counterpart (see Section 3.3) hereafter we refer to it as the ‘SE outer relic lobe’.

Corresponding emission on the NW side was very faint, and so we present the smoothed 325 MHz image of a larger region of the sky in Figure 2 (bottom panel). In addition to the SE outer relic lobe and middle lobes, an emission blob located NW of the middle lobes shows a north-south elongation similar to that seen in NVSS. Detailed comparison of its structure from all the three images available (325 MHz with a beam of 9 arcsec (red contours), 325 MHz with a beam of 45 arcsec (thick black contours) and 1400 MHz with a beam of 45 arcsec (blue contours)) is shown in the inset image. Although the overall orientation matches, the location of the emission peaks does not match, demonstrating the diffuse nature of the blob, and hence explaining why it was missed in the high angular resolution (beam ~ 5 arcsec) FIRST data. This diffuse nature along with the lack of any potential optical counterpart (see Section 3.3) suggests that it is not an independent radio source. Hereafter we refer to this as ‘NW outer relic lobe’.

These relic lobes are quite asymmetric in terms of their location with respect to the host galaxy, radio flux densities and orientation with respect to the inner and middle lobes. There is no signature of any more diffuse emission apart from the lobes described here. Note that a compact radio source seen on the SE corner of the image is an unrelated source with a clear optical counterpart. The structure of these two relic lobes neither bear similarity with typical radio lobes nor with the partial shell-like structures of double radio relics found in clusters (e.g. Bagchi et al. 2006). Hence we believe that both these diffuse radio blobs are due to an earlier episode of jet-activity of the AGN hosted in Specu. However, we can not completely rule out an origin for this diffuse emission by some independent radio-loud AGN or other cluster related phenomena.

The largest angular separation between these two relic lobes (570 arcsec) corresponds to ~ 1.3 Mpc, classifying Specu as a giant (old) radio galaxy (see Schoenmakers et

al. 2001). These three distinct pairs of lobes are probably produced by three different episodes of radio-jet activity of the AGN in Specu. If confirmed, this will be the second triple-double radio galaxy after B0925+420 (Brocksopp et al. 2007). Multiple episodes of jet activity may be correlated with the recent ($\lesssim 500$ Myr) star formation seen in the host galaxy (see Section 3.1). Since these relic lobes could be several 100s of Myr old and the few detections of them so far are believed to be the “tip of the iceberg” (Dwarakanath & Kale 2010), upcoming sensitive low frequency surveys (e.g. TGSS: TIFR GMRT Sky Survey at 150 MHz or surveys from LOFAR: Low Frequency Radio Array) will possibly discover many more examples to help understand the duty cycle of AGNs, black hole coalescence (Liu 2004), and the role of AGN-feedback in galaxy and cluster evolution (Croton et al. 2006).

3.3 Revived relic lobes in a cluster

Specu belongs to a cluster of galaxies MaxBCG J212.45357-03.04237, having 14 members within r_{200} (Koester et al. 2007). While spectroscopic redshifts are available for only five other members in NED (Figure 2 bottom panel), we searched the SDSS database for further possible member galaxies with $0.135 < z_{\text{photo}} < 0.141$ and within a radius of 8 arcmin (~ 1 Mpc for the distance of Specu). We found nearly 60 members (marked by triangles in Figure 2 bottom panel), further supporting the presence of a cluster of galaxies. The maximum velocity difference of ~ 1000 km s⁻¹ between confirmed members also supports the presence of a cluster of galaxies around Specu. Although X-ray emission from this region has not been detected by the ROSAT All Sky Survey, we calculate that a 3σ upper limit corresponds to a luminosity of 7×10^{43} erg s⁻¹ and it is still consistent with the presence of a hot intra-cluster medium around Specu. There is no member galaxy located in the middle of the diffuse emission. Furthermore, by searching in the SDSS and NED database without any redshift constraints, we do not see any extended optical source (> 2 arcsec) brighter than -18 in absolute r' -band magnitude (assuming SDSS z_{photo}) and potential radio-loud AGN host galaxy (red in the colour magnitude diagram) within the region of the diffuse lobes.

To understand the physical properties we investigated the spectral index and polarisation of the relic lobes. The two point spectral index of the NW relic, which has $S_{325} = 46$ mJy (from GMRT) and $S_{1400} = 28.45$ mJy (from NVSS), is very flat ($\alpha = -0.32$, where $S_\nu \propto \nu^\alpha$). There is no chance of missing flux in our measurements at 325 MHz with the GMRT, for this small lobe of nearly 3 arcmin size. Although the spectrum of the relic lobe should be confirmed by UV-matched imaging at multiple frequencies, flattening is significant and unlikely have been caused by synthesis imaging issues or the 5-10 per cent absolute flux density calibration errors. On the other hand if NVSS has missed flux, then the true spectral index will be even flatter than -0.32. So, although the exact value of the spectral index ($\alpha = -0.32$) may not be accurate, its true spectral index has to be, we believe, flatter than typical cluster radio relics or relic lobes, which are usually steeper than -1 (Ensslin et al. 1998, Dwarakanath & Kale 2009). Therefore, we propose that such a flat spectral index of the NW relic lobe has been caused by particle

re-acceleration process (Brunetti et al. 2008, van Weeren et al. 2010).

In NVSS, the SE middle lobe and the SE outer relic lobes are not well separated. Their total flux density is 108 mJy at 1400 MHz. However, from the FIRST image we see only the SE middle lobe, and its flux density is 24 mJy. Subtracting this value from the total flux density of the SE middle and the SE outer lobes we calculate the flux density for the SE outer relic to be 84 mJy at 1400 MHz. From the high resolution GMRT measurements, the flux density of SE relic lobe at 325 MHz is 250 mJy. The resulting two point spectral index of the SE relic lobe is -0.75 , which is ~ 0.2 flatter than that of the middle lobes (-0.92 for NE and -0.98 for SW lobes between 1400 MHz (FIRST) and 325 MHz). This spectral index of the SE relic is also flatter than what is expected for such diffuse relic lobes at a similar redshift (e.g. Dwarakanath & Kale 2009). So, some degree of particle re-acceleration is also required in the SE relic lobe. The SE relic lobe shows a sharp linear edge and drops in surface brightness on the edges. The fraction of polarized flux density, measured in NVSS, is 19 per cent, strongly suggesting ordering of the magnetic field due to large-scale linear compression, like in shocks (Ensslin et al. 1998, van Weeren et al. 2010).

The orientation of these elongated outer relic lobes shows little relation with the jet direction of the middle lobes. In the absence of an X-ray image, the structure of the relics can be compared with the galaxy distribution in the cluster. All the five bright, spectroscopically confirmed members are seen to the NE of Specia and seem to be early-type galaxies based on their morphology and red optical colour ($u'-r'$). Specia is the largest and most dominant member of the cluster but the distribution of all possible sixty member galaxies does not show a higher concentration around it (Figure 2 bottom panel). This distribution suggests Specia to be in a dynamically young cluster, possibly related to either a merger or accretion from galaxy filaments. A cluster-merger seems to be unlikely a cause, as the distribution of member galaxies does not show a double peak. Furthermore, the morphology of the relic lobes does not resemble a case where arc-like radio emission is seen perpendicular to the elongated X-ray emission or double-peaked galaxy distribution of the merging clusters (Bagchi et al. 2006, van Weeren et al. 2010). Any cluster-cluster merger along the line of sight can also be ruled out since the relics are widely separated (~ 1.3 Mpc) as seen in projection. Therefore, we speculate that the relic lobes are most plausibly revived by shocks at the cluster outskirts due to cosmological accretion from galaxy filaments (Ensslin et al. 1998; Pfrommer et al. 2008). Numerical simulations predict two locations of such accretion shocks, one near the virial radius (R_{vir}) and the other at $\sim 3R_{vir}$ (Molnar et al. 2009 and references there in). Following the formula from Girardi et al. (1998), a rough estimate of the projected velocity dispersion ($\sim 300 \text{ km s}^{-1}$) of the spectroscopic members leads to a R_{vir} of ~ 850 kpc. Since re-accelerated relic lobes can be expected at diametrically opposite ends of the cluster, the expected separation is ~ 1.7 Mpc. Given the unknown orientation of the relic lobes to the line of sight, the largest separation of 1.3 Mpc between the relic plasma is consistent with it tracing the accretion shock at the virial radius of this cluster.

Since the cluster is possibly dynamically young and

Specia is the brightest cluster galaxy (BCG) with young star formation, as argued in similar BCGs (McNamara et al. 1996, Hicks, Mushotzky & Donahue 2010), we speculate that, alternatively to a galaxy merger origin, Specia could be accreting cold gas from the surrounding intra-cluster medium. Such young star-forming radio galaxies may be a ‘missing link’, as they are rare in the nearby Universe but likely common at higher z (Norris et al. 2007, Zirm et al. 2005). Galaxy mergers and/or cold gas accretion are likely to be correlated with the multiple episodes of AGN jet activity we see in Specia. Most UV-bright young star formation seen in early-type galaxies is interpreted as residual star formation or incomplete quenching of the star formation by past AGN feedback (Schawinski et al. 2007). If this is the case, then the multiple episodes of feedback seen in Specia with an unusual host galaxy are a unique laboratory to investigate the galaxy-black hole co-evolution process in action, and an opportunity for near-field cosmology studies.

ACKNOWLEDGMENTS

We are grateful to the referee, William Keel, for helpful comments. We thank the staff of the GMRT who made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research, India. We thank the staff and observers at Lulin Observatory, National Central University, Taiwan. We are grateful to SDSS, GALEX, NVSS and FIRST surveys, and NED database. AH is grateful to Yen-Ting Lin for his help in searching SDSS. SCR was supported by the National Research Foundation of Korea to the Center for Galaxy Evolution Research.

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